

# Impact of a High Rice Husk Ash Replacement Ratio on Concrete's Strength Performance

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**Abstract.** Cement is the main component of concrete, which is the most widely used construction material worldwide. However, cement production is one of the major sources of carbon dioxide (CO<sub>2</sub>) emissions, causing significant environmental problems. Reducing these emissions, conserving natural resources, and improving the sustainability of concrete structures have motivated researchers to seek alternative cementitious materials. Recently, partial replacement of cement with supplementary cementitious materials (SCMs), particularly agricultural by-products, has gained considerable attention. The use of SCMs not only reduces waste disposal in landfills but also improves the fresh and hardened properties of concrete. Through pozzolanic reactions with cement hydration products, these materials produce calcium silicate hydrate (C-S-H), which enhances concrete strength and durability while reducing production costs. Rice husk ash (RHA) is one such promising material. This study investigates the chemical composition of RHA, as well as its effects on specific gravity, workability, compressive strength, and splitting tensile strength of blended cement concrete compared to conventional concrete. All mixes were prepared with a water-cement ratio of 0.5. Workability was evaluated using the slump test. Cement was partially replaced with RHA at levels of 0%, 5%, 10%, 15%, 20%, 30%, 40%, 50%, 60%, and 70%. Concrete specimens were tested at curing ages of 7, 28, and 91 days. The results indicate that the optimum cement replacement level is 15% RHA, which achieved a compressive strength of 63.10 MPa at 28 days—approximately 24.12% higher than the control concrete (47.88 MPa). Moreover, even at a high replacement level of 60%, the RHA concrete exhibited a compressive strength of 50.62 MPa at 28 days, representing an increase of 5.41 MPa compared to the control mix. These findings demonstrate that rice husk ash, containing highly reactive particles ranging from amorphous to crystalline forms with appropriate particle size, can significantly enhance concrete strength even at high cement replacement ratios.

**Key words:** Concrete; Rice Husk Ash (RHA); Specific Gravity; Supplementary Cementitious Materials (SCM); Calcium Silicate Hydrate (C-S-H); Amorphous; Crystalline.

## 1. Introduction

Portland cement is one of the most widely used materials in the world. Concrete, as a construction material, has proven over time to be superior in terms of performance, durability, form, and versatility. However, the cement production industry is responsible for a significant portion of global carbon dioxide (CO<sub>2</sub>) emissions, contributing approximately 7% of total global CO<sub>2</sub> emissions, according to the Global Cement and Concrete Association. Global cement production continues to increase annually, reaching nearly four billion tons in 2024 (Statista). Cement manufacturing consumes large quantities of natural resources and requires high energy input, resulting in substantial emissions of carbon dioxide (CO<sub>2</sub>), nitrogen oxides, sulfur oxides, and particulate matter. On average, the production of one ton of cement requires approximately 1.7 tons of raw materials, primarily limestone, and generates considerable greenhouse gas emissions (Van Oss and Padovani., 2003). These emissions negatively impact the environment and significantly contribute to global warming. Therefore, improving cement manufacturing technologies and reducing cement consumption through

the use of supplementary cementitious materials (SCMs) are essential strategies for cleaner production and sustainability.

Research on environmentally friendly construction materials, particularly SCMs, has become increasingly important in modern concrete technology. Numerous studies have focused on partially replacing Portland cement with alternative materials such as fly ash, ground granulated blast furnace slag, rice husk ash, corn cob ash, metakaolin, coconut shell ash, groundnut husk ash, volcanic ash, and glass waste powder (Abdulazeez et al., 2019). The use of SCMs aims to reduce the environmental impact associated with cement production while maintaining or enhancing the mechanical and durability properties of concrete. Pozzolanic materials, as defined by the American Society for Testing and Materials (ASTM, 2006), are siliceous or siliceous–aluminous substances that possess little or no cementitious properties on their own. However, when finely divided and in the presence of moisture, they chemically react with calcium hydroxide at ambient temperature to form compounds with cementitious properties. Incorporating pozzolanic materials into concrete can improve strength development, durability, and long-term performance.

Rice husk ash (RHA) is an artificial pozzolan that is inexpensive, widely available, sustainable, and locally produced. Its pozzolanic activity is mainly attributed to the presence of highly reactive amorphous silica. During cement hydration, this silica reacts with calcium hydroxide to form additional calcium silicate hydrate (C–S–H), which is the primary phase responsible for improved concrete strength and durability (Rasoul et al., 2017). Globally, annual rice production exceeds 750 million tons, generating approximately 150 million tons of rice husk as a by-product (Kordi and Salo, 2024). Rice husk typically contains 15–25% silica by weight; when burned under controlled conditions to produce RHA, the silica content can increase to approximately 90% or higher (Hamidu et al., 2025). Due to this high silica content, RHA has attracted considerable interest as a supplementary cementitious material. Several studies have investigated the effects of RHA-blended cement on concrete properties, including strength and durability. Mehta (1978) reported that concrete containing up to 50% RHA exhibited higher strength than ordinary Portland cement (OPC) concrete even at early ages. Similarly, Isaia et al. (2003) found that replacing 50% of cement with RHA produced concrete with strength comparable to OPC concrete. Khassaf et al. (2014) observed that cement replacement levels of 10% and 20% RHA yielded optimal strength performance. However, other researchers reported that the maximum beneficial replacement level was approximately 15% (De Sensale, 2010)(Saraswathy and Song., 2007).

Although previous studies have examined the influence of RHA on various concrete properties, limited research has focused on the combined effects of RHA chemical composition, specific gravity, workability, and high cement replacement ratios on concrete strength. Therefore, this study aims to investigate the mechanical performance of concrete incorporating high levels of RHA as a partial replacement for Portland cement. The workability, compressive strength, and splitting tensile strength of the concrete were evaluated. The findings of this research are expected to support the broader application of rice husk ash in sustainable concrete production by providing a deeper understanding of its material characteristics and performance.

## 2. Materials and experimental work

### 2.1 Cement

In this experimental study, ordinary Portland cement of type CEM I 52.5N was used. The cement was supplied by CEMEX UK Cement Ltd., and its physical and chemical properties were provided by the manufacturer in accordance with BS EN 197-1:1996. The specifications of the cement are summarized in Table 1.

**Table 1. Specification of high strength cement type CEM I 52.5N according to manufacturer (CEMEX UK Cement Ltd).**

Physical properties			Chemical composition										
Specific surface area	Initial setting time	Expansion	Oxides	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	Na <sub>2</sub> O	SO <sub>3</sub>	Cl <sup>-</sup>	FI	LOI*
0.415m <sup>2</sup> /g	130 minutes	1mm	%wt.	19.7	4.7	3.1	63.9	1.1	0.69	3.3	0.05	3.4	2.8

## 2.2 Rice Husk Ash (RHA)

Three different types of rice husk ash, designated as RHA-A, RHA-B, and RHA-C, were used as supplementary cementitious materials (SCMs). The RHA samples were tested to determine their physical and chemical characteristics, including specific surface area, particle size distribution, chemical composition, pozzolanic reactivity, and loss on ignition (LOI). The test results are presented in Tables 2. The physical properties of the RHA samples indicate noticeable differences in specific surface area and mean particle size, which are expected to influence the pozzolanic reactivity and performance of the blended cement concrete. Chemical composition analysis using X-ray fluorescence (XRF) revealed that all RHA samples contained high silica content, confirming their suitability as pozzolanic materials.

**Table 2. Physical properties and chemical composition of the RHA samples based on the X-ray fluorescence test results.**

RHA	Physical properties		Oxides - Chemical composition (% wt. of ash)								
	Specific surface area (m <sup>2</sup> /g)	Mean particle size (μm)	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	K <sub>2</sub> O	P <sub>2</sub> O	SO <sub>3</sub>	MnO	LOI*
RHA-A	0.5375	23.397	92.10	1.06	0.24	0.71	1.36	0.40	0.07	0.11	3.80
RHA-B	0.5871	20.948	89.31	1.39	0.39	0.98	1.81	0.74	1.10	0.16	5.10
RHA-C	0.6927	15.804	84.30	1.06	0.17	0.73	1.52	0.67	0.08	0.14	11.35

## 2.3. Superplasticizer

The incorporation of rice husk ash in cementitious systems generally increases water demand due to its porous structure, angular particle shape, and high specific surface area (Cordeiro et al., 2011). To maintain adequate workability while reducing water content, a polycarboxylate-based superplasticizer (SP) was used in this study. The superplasticizer was supplied by Fosroc International Ltd., and according to the manufacturer, it provides high dispersion efficiency, consistent performance, and long-range water-reducing capability. The product complies with EN 934-2, and its properties are listed in Table 3.

**Table 3. Properties of Fosroc Auracast 200 according to the manufacture (Fosroc International Ltd).**

Nature	Liquid
Color	Dark Straw
Specific gravity	1.050 – 1.070
PH	4 +/- 1
Chloride content	<0.1%
Na <sub>2</sub> O equivalent	<0.5%
Freezing point	
Air entrainment typically less than 2% additional air is entrained at normal dosage	

## 2.4. Aggregates

### 2.4.1. Fine Aggregate

Fine aggregate conforming to BS EN 12620:2013 was used. The grading of the sand was determined through sieve analysis, and the results are presented in Table 4. The fine aggregate exhibited suitable particle size distribution for concrete production.

### 2.4.2. Coarse Aggregate

The coarse aggregate consisted of locally sourced natural uncrushed gravel with particle sizes ranging from 4 to 9 mm. The aggregate had a specific density of 2678 kg/m<sup>3</sup>. The grading and physical properties of the coarse aggregate are summarized in Table 5.

**Table 4. Properties of Fine Aggregate (Sand)**

Sieve	Weight (g)	Percentage (%)	Cumulative passing (%)
4.0mm	11	2.2	97.8
2.8mm	43	8.6	89.2
1.4mm	97	19.4	69.9
600 $\mu$ m	140	27.9	41.9
300 $\mu$ m	159	31.7	10.2
150 $\mu$ m	45	9.0	1.2
75 $\mu$ m	4.0	0.8	0.4

**Table 5. Properties of Coarse Aggregate (Gravel)**

Sieve	Weight (g)	Percentage (%)	Cumulative passing (%)
9.5mm	15	3.00	97.1
8.0mm	48	9.60	87.5
4.0mm	34	68.1	19.4
Pan	97	19.4	0.00

## 2.5. Mixture Proportions

The control concrete mixture was designed to achieve a characteristic compressive strength of 50 MPa using the DOE mix design method (Dewar, 2003). A constant water-to-binder ratio (w/b) of 0.50 was maintained for all mixtures. One control mix was prepared using 100% Portland cement, while the remaining mixes incorporated rice husk ash as a partial replacement for cement at replacement levels of 0%, 5%, 10%, 15%, 20%, 30%, 40%, 50%, 60%, and 70% by weight of binder. For each mixture, nine cube specimens with dimensions 100 × 100 × 100 mm were cast to determine compressive strength at different curing ages. In addition, three cylindrical specimens measuring 100 mm in diameter and 200 mm in height were prepared for each mix to evaluate splitting tensile strength at 28 and 91 days.



**Fig 1. Casting of cubes and cylinders for compressive and splitting tensile strength of concrete, compressive and splitting tensile strength test according to BS EN 12390-3:2009.**

An increase in RHA content resulted in reduced workability and a tendency toward dry concrete mixes. Therefore, superplasticizer was added to improve fluidity. The dosage of superplasticizer was selected in accordance with the manufacturer's recommendations (Fosroc International Ltd.). The total quantity of superplasticizer was calculated as a percentage of the total binder content and was

deducted from the mixing water. The detailed mix proportions for the control and RHA concrete mixtures are presented in Table 6.

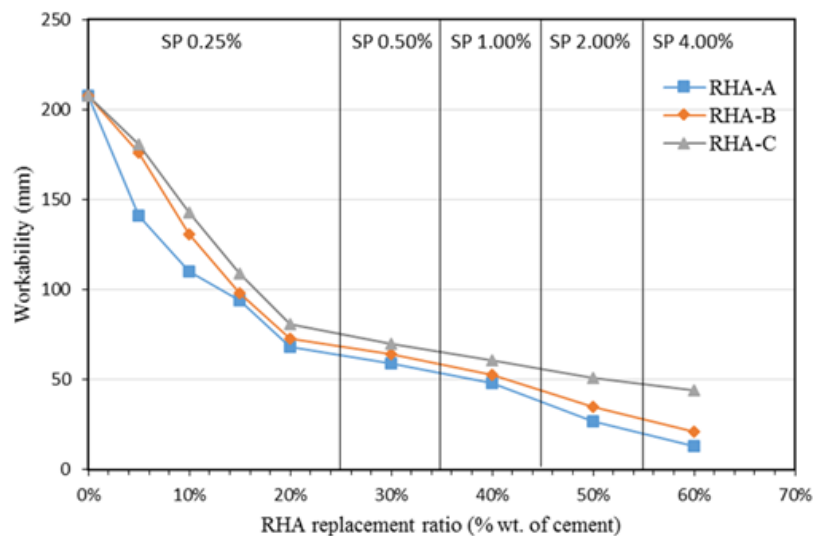
**Table 6. Details of the RHA concrete mixture proportions.**

RHA%	Cement (kg/m <sup>3</sup> )	RHA (Kg/m <sup>3</sup> )	Aggregate (kg/m <sup>3</sup> )		Water (kg/m <sup>3</sup> )	SP (%wt.binder)	SP (kg/m <sup>3</sup> )
			Fine	coarse			
0%	460	0	785	800	228.85	0.25	1.15
5%	437	23	785	800	228.85	0.25	1.15
10%	414	46	785	800	228.85	0.25	1.15
15%	391	69	785	800	228.85	0.25	1.15
20%	368	92	785	800	228.85	0.25	1.15
30%	322	138	785	800	227.70	0.50	2.30
40%	276	184	785	800	225.40	1.00	4.60
50%	230	230	785	800	220.80	2.00	9.20
60%	184	276	785	800	211.60	4.00	18.4
70%	138	322	785	800	202.40	6.00	27.6

### 3. Results

#### 3.1 Influence of RHA Content on Workability

In general, the incorporation of rice husk ash significantly affects the total surface area of the binder, as illustrated in Fig. 2. For example, when RHA-A was used at a replacement level of 5%, the total specific surface area of the blended binder reached 0.4164 m<sup>2</sup>/g, compared with 0.4272 m<sup>2</sup>/g and 0.4289 m<sup>2</sup>/g for RHA-B and RHA-C, respectively. At a replacement level of 60% RHA-C, the total surface area increased by approximately 28.6%, reaching 0.5812 m<sup>2</sup>/g. This increase in surface area becomes more pronounced as the RHA replacement ratio increases. Moreover, the porous structure and irregular particle shape of RHA further reduce the workability of concrete mixtures when the total mixing water content is kept constant. Similar observations were reported by Lu et al. (2016). Among the three RHA types, mixtures containing RHA-C generally exhibited higher workability than those incorporating RHA-A or RHA-B at the same replacement level. This behavior is attributed to differences in particle size distribution and morphology, despite RHA-C having a relatively high loss on ignition (LOI), finer particles, and a higher specific surface area.



**Fig 2. Workability of fresh RHA mixtures at different replacement ratio.**

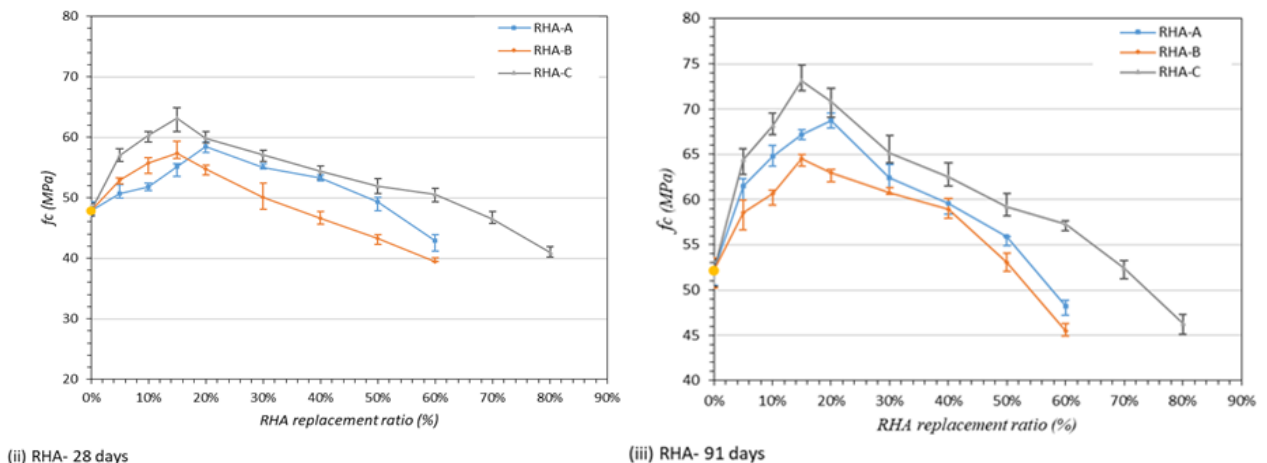
### 3.2. Effect of RHA on Concrete Strength

#### 3.2.1. Effect of RHA Particle Fineness

The fineness of RHA particles has a significant influence on their specific surface area and, consequently, on the pozzolanic reaction and cement hydration process in blended cement systems. These reactions directly affect the development of compressive strength in concrete. The pozzolanic reaction between RHA and calcium hydroxide produces additional calcium silicate hydrate (C-S-H), which refines the pore structure of the cement matrix surrounding RHA particles. Finer RHA particles accelerate the pozzolanic reaction and lead to the formation of smaller calcium hydroxide crystals. Increased fineness enhances the consumption of  $\text{Ca}(\text{OH})_2$  and promotes the formation of C-S-H gel, resulting in improved compressive strength (Chik et al., 2011). Additionally, fine RHA particles act as micro-fillers, contributing to a denser cement paste microstructure and improved strength development (Ismail, and Waliuddin, 1996.).

#### 3.2.2. Effect of RHA Content on Compressive Strength

The influence of RHA content on the compressive strength of concrete at different curing ages is presented in Fig. 3 and Table 7. At early ages (7days), an increase in RHA content generally resulted in a reduction in compressive strength. This behavior is attributed to the delayed pozzolanic reaction, which initiates only after sufficient calcium hydroxide is released during cement hydration (Givi et al., 2010). The pozzolanic reaction involves the interaction between silica from RHA and calcium hydroxide, forming additional C-S-H gel after approximately 40 hours of hydration (Hwang, and Tsai., 2011). As a result, concrete containing RHA tends to be more permeable at early ages but gradually becomes denser than conventional concrete over time. This phenomenon is explained by two main factors: (1) RHA particles initially act as nucleation sites for early hydration products, which may hinder the pozzolanic reaction, and (2) the dissolution of the glassy silica phase depends strongly on the alkalinity of the pore solution, which increases only after several days of hydration (Ismail, and Waliuddin., 1996.).



**Fig 3. Compressive strength results of RHA concrete compared to OPC concrete at curing ages of 28 and 91 days**

Despite this early-age strength reduction, concrete mixtures containing up to 15% RHA exhibited satisfactory performance in 7 days. This early strength improvement can be attributed primarily to the filler effect of fine RHA particles (Antiohos et al., 2013). Previous studies have also reported that reactive silica contributes to strength development mainly at later hydration stages due to porosity reduction (Feng et al., 2006)(Zhang et al., 2000). At 28 days, the beneficial effects of RHA became more pronounced. The compressive strength of RHA concrete exceeded that of the control OPC concrete even at high replacement levels, such as 60% RHA-C, 50% RHA-A, and 30% RHA-B. Notably, concrete containing 60% RHA-C exhibited a 9.01% increase in compressive strength compared to the reference concrete, indicating that cement replacement levels up to 60% can be achieved without adversely affecting strength development. The fine particles of RHA-C improve the particle packing

density within the cementitious matrix, reducing voids and enhancing the microstructure through the filler effect. In addition, the high silica content of RHA-C promotes pozzolanic reactions with calcium hydroxide produced during cement hydration, leading to the formation of additional calcium silicate hydrate (C-S-H) gel, which contributes to strength enhancement and matrix densification. The fineness of the RHA-C particles also increases the surface area available for hydration and pozzolanic interaction, accelerating secondary hydration processes. Furthermore, the porous nature of RHA-C may provide an internal curing effect by retaining and gradually releasing moisture during hydration, thereby improving hydration efficiency and reducing microcracking associated with self-desiccation. The synergistic interaction of these mechanisms collectively contributes to the observed improvement in compressive strength and overall concrete performance.

Although RHA-C exhibited the highest Loss on Ignition (LOI) value, it also demonstrated the best compressive strength performance. This indicates that the higher LOI did not adversely affect the concrete properties. The improved strength can be attributed to the combined effects of the high pozzolanic reactivity, finer particle size, and filler effect of RHA-C, which contributed to a denser microstructure and enhanced bonding within the cement matrix. In addition, the unburnt carbon associated with the higher LOI was likely present in a stable and limited form that did not significantly interfere with cement hydration. Therefore, the beneficial effects of RHA-C outweighed the potential negative influence of its higher LOI value.

**Table 7. Compressive strength results of OPC and RHA concrete at different curing ages (7,28, and 91 days).**

RHA%	Compressive strength (MPa)								
	Age 7 days			Age 28 days			Age 91 days		
	RHA-A	RHA-B	RHA-C	RHA-A	RHA-B	RHA-C	RHA-A	RHA-B	RHA-C
5%	38.22	43.23	46.64	50.68	52.87	56.97	61.53	58.53	64.43
10%	37.90	40.95	43.11	51.77	55.73	60.27	64.83	60.63	68.17
15%	35.70	35.91	37.59	55.14	57.32	63.1	67.2	64.53	73.11
20%	34.08	32.27	34.57	58.47	54.73	59.84	68.73	62.96	70.83
30%	29.37	30.41	32.86	54.95	50.10	57.11	62.37	60.77	65.20
40%	27.33	23.93	28.82	53.27	46.63	54.34	59.60	58.93	62.50
50%	25.88	20.33	26.09	49.36	43.31	51.9	55.87	53.07	59.23
60%	17.28	13.78	18.01	42.96	39.49	50.6	48.21	45.46	57.29
70%	-	-	14.25	-	-	46.55	-	-	52.41
OPC	35.16			47.88			52.10		

### 3.3.3. Effect of RHA Content on Splitting Tensile Strength

The splitting tensile strength results of RHA concrete at 28 and 91 days are presented in Table 8 and Fig. 4. The tensile strength increased gradually with increasing RHA content up to optimal replacement levels. Maximum splitting tensile strength was achieved at 15% RHA-B and RHA-C and 20% RHA-A. For example, the mixture containing 15% RHA-C exhibited a 30.91% increase in splitting tensile strength compared to the OPC control concrete at 28 days. At higher replacement levels, such as 40% RHA-B and RHA-C and 30% RHA-A, the tensile strength values were comparable to those of concrete with 5% RHA replacement.

At very high replacement ratios (60% RHA-A and RHA-B, and 70% RHA-C), the splitting tensile strength was either equivalent to or slightly lower than that of the OPC control concrete. This behavior may be attributed to an excess of available silica relative to the amount of calcium hydroxide produced, resulting in incomplete pozzolanic reactions. These findings are consistent with the results reported by Isaia et al. (2003), who observed improved long-term strength in concrete incorporating high levels of RHA.

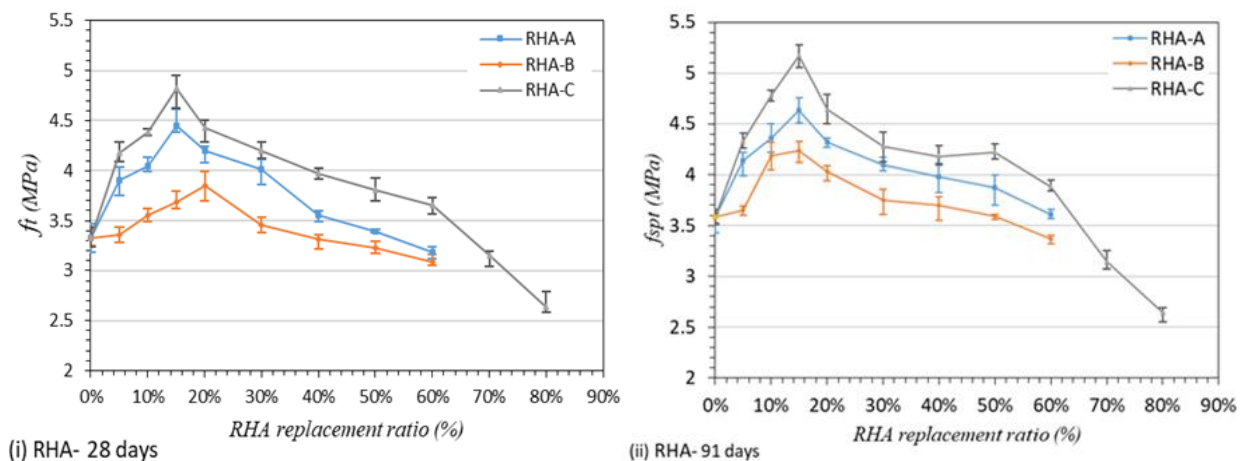


Fig 4. RHA concrete splitting tensile strength development at the age of; (i) 28 days, (ii) 91 days).

Table 8. Tensile strength results of OPC and RHA concrete at different curing ages (28, and 91 days).

RHA%	Tensile strength (MPa)					
	Age 28 days			Age 91 days		
	RHA-A	RHA-B	RHA-C	RHA-A	RHA-B	RHA-C
5%	3.9	3.36	4.18	4.14	3.65	4.33
10%	4.05	3.55	4.39	4.36	4.19	4.78
15%	4.2	3.85	4.82	4.63	4.24	5.17
20%	4.41	3.69	4.59	4.72	4.03	4.94
30%	4.01	3.46	4.2	4.31	3.75	4.58
40%	3.65	3.31	3.97	3.98	3.7	4.37
50%	3.39	3.23	3.81	3.87	3.59	4.22
60%	3.18	3.09	3.65	3.61	3.37	3.88
70%	-	-	3.15	-	-	3.74
OPC	3.34			3.61		

#### 4. Discussion of the results

The experimental results presented in Tables 7 and 8 and Figs. 3 and 4 clearly demonstrate that the incorporation of rice husk ash significantly enhances the mechanical properties of concrete, particularly compressive and splitting tensile strength, at curing ages of 28 and 91 days. The observed strength improvement is primarily attributed to the pozzolanic activity and micro-filling effect of RHA. The finer particle size of RHA-C enables it to effectively fill micro-voids within the cement matrix, leading to improved particle packing density. According to Sawayama, et al. (1999), RHA readily reacts with water and calcium hydroxide, a by-product of cement hydration, to form additional calcium silicate hydrate (C-S-H). Since C-S-H is the principal phase responsible for strength development in concrete, its increased formation results in enhanced mechanical performance.

Furthermore, the additional C-S-H gel fills capillary pores, thereby reducing concrete porosity and improving the microstructure of both the bulk paste and the interfacial transition zone. This densification process contributes to the observed increase in compressive and tensile strength. It should be noted that all specimens in this study were cured under standard conditions. The internal curing effect of RHA, combined with its silica structure and filler action, is believed to play a key role in strength enhancement, particularly at high cement replacement ratios. The use of RHA with smaller particle size, such as RHA-C, enhances the packing density of the granular mixture, which in turn increases the final strength of concrete. At replacement levels up to 15%, all RHA mixtures exhibited improved compressive strength at 7 days. However, beyond this level, early-age strength decreased

due to the absorption of mixing water by RHA particles, which reduced the amount of free water available for cement hydration. Over time, the absorbed water contributes to continued hydration, resulting in improved long-term strength development.

The combined effects of micro-filling and pore refinement are primarily responsible for the strength enhancement observed in RHA concrete, particularly for RHA-C, as the curing period increases to 28 and 91 days. The superior performance of RHA-C can be attributed to its high proportion of ultra-fine particles, with approximately 9.75% of particles measuring 0.06  $\mu\text{m}$ , which significantly improves both packing density and pozzolanic reactivity. Despite their relatively coarser particle size and higher crystalline silica content, RHA-A and RHA-B also enhanced concrete strength at replacement levels of up to 50% compared to the control concrete. This improvement is mainly attributed to the presence of amorphous silica and, to a lesser extent, the fine particle fraction within these RHA types. The combined influence of chemical composition and particle size distribution plays a crucial role in determining the effectiveness of RHA as a supplementary cementitious material. Overall, the findings confirm that rice husk ash, when properly processed and characterized, can be effectively used at high cement replacement ratios without compromising concrete strength, thereby offering a sustainable and environmentally friendly alternative to conventional Portland cement.

## 5. Conclusions

Based on the experimental investigation of concrete incorporating rice husk ash (RHA) as a partial replacement for Portland cement, the following conclusions can be drawn:

- i. Rice husk ash exhibits strong pozzolanic activity due to its high silica content and fine particle size, which significantly influences the mechanical performance of concrete, particularly at later curing ages.
- ii. The workability of fresh concrete decreases with increasing RHA replacement ratios because of the porous structure, angular particle shape, and high specific surface area of RHA. However, the use of an appropriate dosage of polycarboxylate-based superplasticizer effectively mitigates this reduction in workability.
- iii. At early ages (7 days), concrete mixtures with higher RHA content generally show lower compressive strength due to the delayed pozzolanic reaction. Nevertheless, mixtures containing up to 15% RHA demonstrated satisfactory early-age strength, mainly due to the filler effect of fine RHA particles.
- iv. Significant improvements in compressive strength were observed on 28 and 91 days. The optimum cement replacement level was found to be 15% RHA, which resulted in the highest compressive and splitting tensile strength among all mixes.
- v. Concrete incorporating RHA-C, characterized by finer particle size and higher specific surface area, showed superior performance compared to RHA-A and RHA.
- vi. Notably, compressive strength enhancement was observed even at high replacement levels of up to 60%, indicating the potential for substantial cement reduction without compromising strength.
- vii. The improvement in strength is primarily attributed to the combined effects of pozzolanic reaction and micro-filling action, which lead to the formation of additional calcium silicate hydrate (C-S-H), reduced porosity, and a denser cement matrix.
- viii. Despite their relatively coarser particle size and higher crystalline silica content, RHA-A and RHA-B also enhanced concrete strength at replacement levels of up to 50%, demonstrating the importance of both chemical composition and particle size distribution in determining RHA performance.
- ix. Overall, rice husk ash proves to be an effective and sustainable supplementary cementitious material, capable of significantly reducing cement consumption and associated CO<sub>2</sub> emissions while maintaining or improving concrete strength.

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